

Low radio frequency signatures of ram pressure stripping in Virgo spiral NGC 4254

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ABSTRACT

We report the detection of extended low radio frequency continuum emission beyond the optical disk of the spiral galaxy NGC 4254 using the Giant Metrewave Radio Telescope. NGC 4254, which has an almost face-on orientation, is located in the outskirts of the Virgo cluster. Since such extended emission is uncommon in low inclination galaxies, we believe it is a signature of magnetised plasma pushed out of the disk by ram pressure of the intracluster medium as NGC 4254 falls into the Virgo cluster. The detailed spectral index distribution across NGC 4254 shows that the steepest spectrum $\alpha < -1$ ($S \propto \nu^\alpha$) arises in the gas beyond the optical disk. This lends support to the ram pressure scenario by indicating that the extended emission is not from the disk gas but from matter which has been stripped by ram pressure. The steeper spectrum of the extended emission is reminiscent of haloes in edge-on galaxies. The sharp fall in intensity and enhanced polarization in the south of the galaxy, in addition to enhanced star formation reported by others provide evidence towards the efficacy of ram pressure on this galaxy. HI 21cm observations show that the gas in the north lags in rotation and hence is likely the atomic gas which is carried along with the wind. NGC 4254 is a particularly strong radio emitter with a power of 7×10^{22} Watts-Hz⁻¹ at 240 MHz. We find that the integrated spectrum of the galaxy flattens at lower frequencies and is well explained by an injection spectrum with $\alpha_0 = -0.45 \pm 0.12$. We end by comparing published simulation results with our data and conclude that ram pressure stripping is likely to be a significant contributor to evolution of galaxies residing in X-ray poor groups and cluster outskirts.

1 INTRODUCTION

Galaxy mergers (Toomre 1977), galaxy harassment (Moore et al. 1996), ram pressure (Gunn & Gott 1972), viscous stripping (Nulsen 1982) and dynamical friction (Lecar 1975, Chandrasekhar 1943) are believed to play a role in the evolution of galaxies in a cluster environment and have explained numerous observational results. Different physical mechanisms dominate in different environments. While ram pressure effects are believed to be dominant in the dense inner regions of clusters, tidal interactions are believed to dominate the evolution in the cluster outskirts and in groups of galaxies. However, this picture has been undergoing a gradual paradigm shift as demonstrated by observations, especially at radio frequencies, and simulations of groups and outskirts of clusters (e.g. Virgo) conducted by various authors.

The Virgo cluster galaxies have been extensively studied in radio and other wavebands e.g. in HI 21cm by Davies, et al. (2004), Cayatte et al. (1990), Warmels (1988), Huchtmeier & Richter (1986) and in radio continuum by Vollmer et al. (2004). Chung et al. (2007) have recently reported HI tails for several Virgo galaxies which they conclude is ram pressure stripped gas from the galaxy. Vollmer et al. (2007) have studied the polarisation properties of sev-

eral Virgo spirals and inferred that the interaction of the galaxy with the intracluster medium (ICM) has resulted in peculiar polarisation properties of the cluster spirals. Wezgoweic et al. (2007) find distorted magnetic fields in several Virgo cluster members which they attribute to ram pressure of the ICM.

NGC 4254 is an interesting almost face-on SA(s)c spiral, located in the outskirts of the Virgo cluster, with one dominant spiral arm. This galaxy has been studied extensively in the HI line (Cayatte et al. 1990, 1994, Phookun et al. 1993), in high frequency radio continuum and polarization (Urbanik et al. 1986, Soida et al. 1996, Urbanik 2004 Chyzy et al. 2006), in X-rays (Chyzy et al. 2006, Soria & Wong 2006) and via simulations involving tidal interaction and ram pressure stripping (Vollmer et al 2005). NGC 4254 is both optically and radio bright and lies about 4° (~ 1.2 Mpc using a distance of 17 Mpc to Virgo cluster) to the north-west of M87. Phookun et al. (1993), from their deep HI observations, separate the disk and non-disk emission from the galaxy and find that the latter forms a tail of clouds that extend to $\sim 11'$ from the galaxy. They conclude that there is an infall of a disintegrating cloud of gas onto NGC 4254 and that the one-armed structure is a result of the tidal interaction with the infalling gas. Vollmer et al (2005) have modelled NGC 4254 after including a tidal encounter and ram pressure

stripping. They find that the one-armed structure can be explained by a rapid and close encounter $\sim 2.8 \times 10^8$ years ago with another massive galaxy ($\sim 10^{11} M_\odot$). They note that most of the observed HI morphology is reproduced by including ongoing ram pressure effects in the simulation and only two main HI features remain unexplained namely 1) the shape of the extended tail of HI emission in the north-west, 2) a low surface density HI blob observed to the south of the main disk. Davies et al. (2004) and Minchin et al. (2005) have reported the detection of a massive ($\sim 10^{11} M_\odot$) HI cloud VIRGOHI 21 in the Virgo cluster. This cloud lies to the north of NGC 4254 and connects both spatially and kinematically to NGC 4254 (Minchin et al. (2005). Recently Haynes et al. (2007) have presented the HI map of this entire region made using the Arecibo telescope. They detect a long HI tail which starts from NGC 4254, includes VirgoHI 21 and extends northwards to a total distance of 250 kpc. Earlier observations had only detected parts of this long HI tail. Haynes et al. (2007) attribute this long HI tail to galaxy harassment (Moore et al. 1996) which the galaxy is undergoing as it enters the Virgo cluster.

Soida et al. (1996), from their radio continuum observations near 5 and 10 GHz, have reported enhanced polarisation in the southern ridge which they attribute to interaction of the disk gas with the ICM. Chyzy et al. (2006,2007) detect an extended polarized envelope at 1.4 GHz. Excess blue emission is observed along the southern ridge (Knapen et al. 2004) which indicates the presence of a large population of young blue stars (Wray 1988). The trigger for the enhanced star formation in this region is possibly compression by the ram pressure of the ICM. From high resolution CO data, Sofue et al. (2003) note that the inner spiral arms of NGC 4254 are asymmetric. They reason that the ram pressure of the ICM has distorted the inter-arm low density regions leading to the asymmetric spiral arms. This galaxy has also been observed in the near and far ultraviolet by GALEX (Gil de Paz et al. 2007). The UV morphology of the galaxy is similar to the DSS optical with several young star forming regions visible in the GALEX images.

In light of all these interesting results, we present new low frequency radio continuum and HI 21cm observations of NGC 4254 using the Giant Metrewave Radio Telescope (GMRT) near Pune in India. The continuum observations were conducted at four frequencies between 240 and 1280 MHz. We detected extended continuum emission surrounding the optical disk of NGC 4254. We discuss the integrated spectrum of the galaxy and the environmental effects on this galaxy located at the periphery of the cluster. We adopt a distance of 17 Mpc to the Virgo Cluster following Vollmer et al. (2005). In Table 1, we summarize the physical properties of NGC 4254 and the empirical data from wavebands ranging from X-rays to radio.

2 OBSERVATIONS AND RESULTS

NGC 4254 was observed at 240 MHz, 325 MHz, 610 MHz and 1280 MHz in the radio continuum and in the 21 cm emission line of HI using the GMRT (Swarup et al. 1991, Ananthakrishnan & Rao 2002). GMRT consists of thirty 45-m diameter parabolic dish antennas spread over a 25 km region and operates at five frequency bands below 1.5 GHz. Details of our observations are listed in Table 2.

Table 1. Properties of NGC 4254

Parameter	Value/Property	Reference
$\alpha(2000)$	$12^h 18^m 49.6^s$	RC3
$\delta(2000)$	$14^\circ 24' 59''$	RC3
Morphological type	Sc	RC3
Optical diameter D_{25}	$5.4'$	RC3
B_T^0	10.44	RC3
Heliocentric velocity	$2407 \pm 3 \text{ kms}^{-1}$	RC3
Distance	17 Mpc	Vollmer et al. (2005)
Distance to cluster centre	$\sim 1.2 \text{ Mpc}$	
From HI		
Morphology	distorted	Cayatte et al. (1990)
V (rotation)	150 kms^{-1}	Phookun et al. (1993)
Inclination angle	42°	Phookun et al. (1993)
Non-disk emission	$2.3 \times 10^8 M_\odot$	Phookun et al. (1993)
HI deficiency	0.17 ± 0.2	Cayatte et al. (1994)
ICM ram pressure	$0.9 \times 10^{-12} \text{ dyn-cm}^{-2}$	Cayatte et al. (1994)
Grav pull	$1.6 \times 10^{-12} \text{ dyn-cm}^{-2}$	Cayatte et al. (1994)
Galaxy Harassment	250 kpc tail	Haynes et al. (2007)
From radio continuum		
Radio spectrum (0.4-10 GHz)	-0.83 ± 0.04	Soida et al. (1996)
Polarised emission	excess in south	Soida et al. (1996)
Polarised envelope	yes	Chyzy et al. (2007)
From Optical (DSS), NIR (2MASS), NUV,FUV (GALEX)		
Structure	One-arm morphology	...
Star formation	Vigorous	...
Blue stars	Forms a ridge in south	Wray (1988)
B Band	Excess in south	Knapen et al. (2004)
From CO		
Inner arms	asymmetric	Sofue et al. (2003)
Possible Reason	ICM ram pressure	Sofue et al. (2003)
From X-ray		
Galaxy	Intense emitter	Fabbiano et al. (1992)
Discrete source	ULX in south	Soria & Wong (2006)
From simulations		
One arm	Tidal	Vollmer et al. (2005)
Obs. HI structure	tidal+ram press	Vollmer et al. (2005)
Stripping angle	70°	Vollmer et al. (2005)

2.1 Radio continuum

The visibility data obtained at GMRT in 'Ita' format were converted to FITS and imported to AIPS¹. The analysis was carried out using standard tasks in AIPS. Since the field-of-view at 610, 325 and 240 MHz is large, the images were generated using multiple facets. The final images were generated using robust weighting (Briggs 1995) of the visibilities. We made the images using robust=0 (between pure uniform weighting i.e. robust= -5 and pure natural weighting i.e. robust= 5) and robust=5.

In Fig. 1, we show the images made using robust=0. A sharp cutoff to the radio emission is observed to the south/south-east (see the 325 and 1280 MHz images in Fig. 1). A radio continuum minimum is detected in the north-west at all frequencies although the extent and shape varies. Part of this difference is likely due to the different spatial frequency coverage of the multi-frequency observations. This minimum is accentuated in the naturally weighted maps with it being most prominent at 240 MHz (see Fig. 3b). The 1280 MHz image (robust=0) was made using a maximum baseline of 14 k λ to highlight the extended features. In Fig. 2, the 610 MHz

¹ AIPS is distributed by NRAO which is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc.

Table 2. Details of radio observations. The integrated flux density of NGC 4254 is given in the last row.

Obs Freq (MHz)	240	325	610	1280	21 cm HI
Obs Dates	20/02/06	24/04/04	20/02/06	23/10/00	16/11/00
Working antennas	23	26	23	18	22
Bandwidth(MHz)	5	9	13	12	0.0625 ¹
Robust=0					
Synthesized Beam	17.7'' × 11.4''	27'' × 10.3''	9.9'' × 5.3''	23'' × 20'' ²	7.5'' × 4.9''
Position angle	−81°	−47°	−87°	−44°	31°
RMS noise (mJy/beam)	1.1	1.0	0.2	0.1	2.3 ³
Robust=5					
Synthesized Beam	24'' × 21''	34'' × 20''	17'' × 16''	19'' × 17''	-
Position angle	−31°	−6°	24°	54°	-
RMS noise (mJy/beam)	0.9	2	0.2	0.15	-
S (Jy)	1.96	1.6	1.08	0.377	-

¹ 128 channels over the 8 MHz bandwidth resulted in this channel width (i.e. 12.5 kms^{−1}).² using data on baselines upto 14kλ.³ rms is for a channel of width 12.5 kms^{−1}.**Figure 1.** Maps of NGC 4254 made using Briggs robust=0. The contours are plotted at 3, 6, 12, 24, 48 and 96 times the rms noise σ . The crosses mark the position of the optical centre of NGC 4254 and the three background point sources in the field. (a) Top left panel. The image at 240 MHz with a beamsize 17.7'' × 11.4'', PA= −81° The rms noise is $\sigma = 1.1$ mJy/beam. The highest contour is 35 σ . (b) Top right panel. The image at 325 MHz. The angular resolution is 27'' × 10.3'', PA= −46.8°. The rms noise is $\sigma = 1$ mJy/beam and the highest contour is 35 σ . (c) Bottom left panel. The image at 610 MHz has a resolution of 9.9'' × 5.3'', PA= −87°. The rms noise is $\sigma = 0.2$ mJy/beam and the highest contour is 24 σ . (d) Bottom right panel. Image at 1280 MHz, obtained with a uv taper of 14kλ along both axes (u,v) and convolved to an angular resolution of 23'' × 20'', PA= −44° to highlight the extended emission in the north-west. The rms noise is $\sigma = 0.1$ mJy/beam and the highest contour is 140 σ .**Figure 2.** The 610 MHz Briggs robust=0 map (in contours) is superposed on the DSS grey scale map. Note the radio envelope around the optical disk. The crosses mark the position of the optical centre of the galaxy and the three background point sources.

image has been superposed on the DSS optical image to show the envelope of radio emission around the optical disk. We note that our images at 240 MHz and 610 MHz made using robust=5 are by far the most sensitive low frequency images of this galaxy with rms noise of 0.9 mJy/beam and 0.2 mJy/beam respectively, for the beamsizes listed in Table 2. The signal-to-noise ratio on the robust=5 image is higher than on the robust=0 image by a factor of about 3. In Fig. 3, the robust=0 and robust=5 images at 240 MHz are shown for comparison. The correlation between the images is good as seen from the radio emission which extends outwards of the optical disk in the north-west, south-east and south-west and is present in both the maps. For rest of the discussion, we use the naturally weighted images at 240 and 610 MHz unless stated.

The integrated flux density of NGC 4254 at different frequencies are listed in Table 2. Visibility data corresponding to the three confusing sources (marked in Fig. 3) which are engulfed by the radio emission from NGC 4254 were removed before generating the images used for constructing the spectral index maps.

2.2 21 cm HI

An 8 MHz bandwidth spread over 128 channels and centred at 2407 kms^{−1} resulted in a channel width of 62.5 KHz ≈ 12.5 kms^{−1} for our HI observations. 3C147 and 1120+143 were used as the flux and phase calibrators respectively. The HI data were analysed in AIPS++ ver 1.9 (build 1460). The continuum was estimated by fitting a first order baseline to the line-free channels and subtracted from the data. A spectral line cube was then generated from this

Figure 4. The HI moment maps are superposed on the 240 MHz grey scale image. (a) Top panel. HI Moment 0 map. The lowest contour level is 3.4×10^{19} cm^{−2}. Contours levels are $(20.4 + 2.43n) \times 10^{19}$ cm^{−2} where n runs from −7 to 7. (b) Middle panel. HI Moment 1 map. The systemic velocity of the galaxy is 2407 kms^{−1}. The solid lines indicate recession while the dashed lines identifies the approaching side. (c) Bottom panel. HI Moment 2 map.

database. The moment maps shown in Fig. 4 were obtained using a rms noise cutoff of 1.5 σ in the channel maps. The full resolution maps had an angular resolution of about 7.5'' × 4.9'' with a position angle of 31°.

The HI distribution (Fig. 4) across NGC 4254 shows emission detected from the disk but little HI is coincident with the radio continuum extensions in the south-east, the north-west and the south-west. The lowest column density is 3.4×10^{19} cm^{−2}. The velocity field (Fig. 4b) shows that the north-east is the receding side of the disk. A slight lopsidedness is visible in the velocity field with the north-east showing lower rotation (< 100 kms^{−1}) velocities compared to the south-west (< -100 kms^{−1}) wrt to the systemic velocity (2407 kms^{−1}) of the galaxy. Fig. 4c shows the velocity dispersion across the galaxy. Widest spectral lines are seen near the centre whereas rest of the disk shows line widths of 10–15 kms^{−1}. The disk has a smooth boundary to the south, south-east whereas the northern boundary is jagged as if this part of HI is being ‘blown’ off. Interestingly, this is also the region where Phookun et al. (1993) detect the largest non-disk HI cloud. We do not detect the non-disk HI clouds (Phookun et al. 1993) or the long HI tail (Haynes et al. 2007) associated with NGC 4254 likely due to lack of short spatial frequencies resulting in lower sensitivity to such extended faint features.

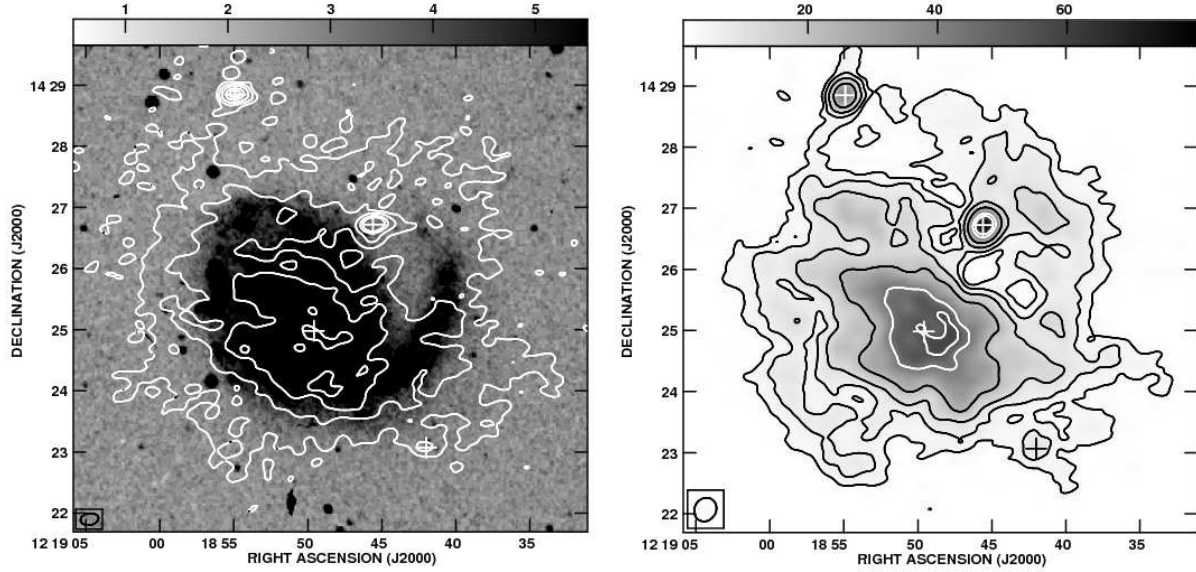


Figure 3. 240 MHz image. Notice the envelope of radio continuum emission at 240 MHz which surrounds the DSS map in the left panel. The contours are plotted at 3, 6, 12, 24, 48 times the rms noise (σ). (a) The 240 MHz map made with robust=0 superposed on the DSS optical map. Angular resolution is $17.7'' \times 11.4''$, PA = -81° . The rms noise is 1.1 mJy/beam. The highest contour is 35σ . (b) The naturally weighted (robust=5) 240 MHz map. The angular resolution is $24'' \times 21''$, PA = -30° . The rms noise is 0.9 mJy/beam. The highest contour is 72σ . The grey scale runs from 0.9 to 80 mJy/beam.

3 THE RADIO MORPHOLOGY

We enumerate below the interesting morphological features detected in the radio continuum emission (Figs. 1, 2, 3) and the HI (Fig. 4) from NGC 4254.

- (i) Radio continuum emission and HI are detected from the optical disk.
- (ii) Bright abrupt cutoff in the radio emission to the south of the galaxy which outlines the optical disk.
- (iii) Low surface brightness emission enveloping the disk emission is detected at all frequencies. These features are prominent at 240 MHz (see Fig. 3). Most notable features are the extension to the north-west, south-east and the finger-like extensions in the south-west which is likely the gas blown out by the ICM pressure. No R band or H α emission is detected from these regions.
- (iv) A minimum in the radio continuum is detected in the north-west at all the frequencies. This minimum is most extended and prominent at 240 MHz. Chyzy et al. (2006,2007) report low polarization in the region which appears to be partially coincident with the minimum at 240 MHz. Thus the minimum could likely be due to a decrease in the magnetic field in that region.
- (v) About 15% of the total emission at 240 MHz arises in the emission which surrounds the optical disk.
- (vi) The HI disk is extended in the north-east (see Fig. 4).
- (vii) The HI velocity field is lopsided. Lower recessional velocities are recorded in the north-east and the same region also shows lower column densities. Moreover, the velocity field in the north appears to lag.
- (viii) The HI has a jagged border in the north, north-west (see Fig. 4) suggesting that the atomic gas is being progressively ‘blown’ off. A smooth boundary is seen in the south, south-east. Moreover the HI shows a vertical edge in the north-east and the west as if gas has been stripped off.

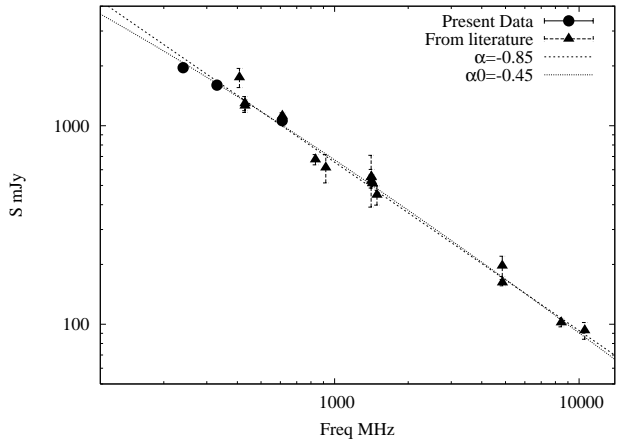


Figure 5. Integrated spectrum of NGC 4254 including the data from Soida et al. (1996) & Chyzy et al. (2007). The best single power law fit to the data has an index $\alpha = -0.848$ and is shown by the dashed line. The dotted line shows the best fit to the data if electron energy losses are included. It has an injection spectrum of -0.45 and has lower χ^2 than the single power law fit. Data at frequencies ≤ 100 MHz are required to confirm the break in the spectrum.

- (ix) HI is not found to be coincident with the radio continuum envelope around NGC 4254 (see Fig. 4).

We compare the radio continuum envelope to the HI low resolution map in Phookun et al. (1993) who detected disk and non-disk HI components. Phookun et al. (1993) inferred that the non-disk HI clouds around NGC 4254 were an infalling population. A similar conclusion can be drawn from the HI velocity field of the non-disk clouds which are likely to be located between us and the galaxy.

The HI blob (Fig 5 in Phookun et al. 1993) to the south of NGC 4254 is coincident with part of southern extension we detect at 240 MHz. Moreover, some of the northern HI clouds are coincident with the northern radio continuum extension (see Fig 3). However, it is not clear if these are physically associated or coincident in projection. The HI velocity field is distorted in the north of the galaxy (Fig 4 (b) in Phookun et al. 1993).

4 THE RADIO SPECTRUM

We estimate a global spectral index between 240 and 610 MHz of -0.65 . However, fitting a single power law using the least squares method to all the available data ranging from 408 MHz to 10 GHz (Soida et al. 1996, Chyzy et al. 2007) and including our data (excluding the 1280 MHz point) resulted in the best fit spectrum with an index of -0.848 ± 0.016 (see Fig 5). This is in good agreement with the value (-0.83 ± 0.04) that Soida et al. (1996) quote. However $\alpha = -0.65$ obtained from our low frequency data suggests that the spectrum might be flattening at the lower frequencies. Since the galaxy is face-on, absorption by foreground thermal gas is expected to be negligible. Thus, the break could possibly be due to propagation effects of relativistic electrons and subsequent energy losses as explained by Pohl et al. (1991) & Hummel (1991).

To check this, we fitted the observed integrated spectrum of NGC 4254 using the heuristic model given by Hummel (1991) which describes the radio spectrum as

$$S(\nu) = K \frac{\nu^{\alpha_0}}{1 + (\nu/\nu_b)^{1/2}} \quad (1)$$

The spectral index of the injection spectrum, α_0 and the break frequency, ν_b are estimated by fitting the observed spectrum with the above function. The best fit which has $\alpha_0 = -0.45 \pm 0.12$ is shown in Fig. 5. This spectrum gives a lower χ^2 compared to the single power law fit (also in Fig. 5) and hence, we believe, is a better fit to the observed data between 240 MHz and 10 GHz. However the fit fails to constrain the break frequency since we do not have data points below 240 MHz. From the above, it is reasonable to conclude that the integrated spectrum of NGC 4254 has a break at lower frequencies which is typical of spiral galaxies (Pohl et al. 1991, Hummel 1991). We also note that lower frequency data ($\nu \leq 100$ MHz) are required to confirm the break.

A spectral index map of NGC 4254 was constructed between 240 and 610 MHz (Fig. 6). Images at both the frequencies were made with a maximum baseline of 15 k λ and then convolved to an angular resolution of $27'' \times 21''$ at a position angle of -24° . A cutoff of 2σ was used for both the images. While the spectral index across the disk is typically between $\alpha = -1$ and -0.4 with few regions showing $\alpha < -1$, the emission outside the optical disk typically has a spectral index steeper than -1 (see Fig. 6). The spectral index of the envelope is reminiscent of the halo emission in edge-on galaxies. Chyzy et al (2006,2007) report the detection of a sharp bright magnetized ridge at 1.43 GHz in the south and present their image at 4.8 GHz. They do not detect the southern feature at 4.8 GHz which implies a spectral index steeper than -1.5 when combined with our 240 MHz data. This is consistent with our data at 610 MHz. The spectral index near the centre of the galaxy is comparable to the disk ruling out the presence of an AGN at the centre.

From the above discussion, we conclude that there are two components to the radio continuum emission from NGC 4254, namely the intense disk component which has $\alpha \geq -1$ and the

extended component which has $\alpha \leq -1$. The two components are difficult to distinguish morphologically.

5 DISCUSSION

The radio power at 1.4 GHz of most normal spiral galaxies lie between 1.6×10^{19} Watts-Hz $^{-1}$ and 10^{22} Watts-Hz $^{-1}$ (Hummel 1981) and absolute blue magnitudes lie between -18 to -21 (Hummel 1981). NGC 4254 has a power of 1.5×10^{22} Watts-Hz $^{-1}$ at 1.4 GHz. The RC3 (de Vaucouleurs et al. 1991) 25 magnitude size of NGC 4254 is $322'' \times 281''$ and its total blue apparent magnitude is 10.44 yielding an absolute magnitude of -21.05 . NGC 4254 is thus, both optically and radio bright. High star formation rates (Schweizer 1976) of $\sim 10 M_\odot \text{yr}^{-1}$ (Soria & Wong 2006) have been reported for NGC 4254. Cayatte et al. (1990) suggested that the sharp cutoff in HI in the south-east could be due to compression by the ICM which could then explain the bright disk. Simulations by Vollmer et al. (2005) suggest that ram pressure needs to be invoked to explain the observed HI morphology. More recently, Chyzy et al. (2006,2007) have detected a large polarized envelope of emission at 1.43 GHz around the optical disk and also a bright ridge of polarised emission in the south which they suggest is due to field compression by ram pressure. This, they suggest, could be enhanced by the non-disk HI clouds detected by Phookun et al. (1993) falling back on the disk. All the above indicate that ram pressure due to interstellar medium (ISM)-ICM interaction is active in this system.

On the other hand, ample evidence that this galaxy was involved in a tidal encounter has been found - the single dominant spiral arm, the presence of non-disk HI clouds (Phookun et al. 1993) and the presence of a large HI tail which extends northwards from NGC 4254 to a distance of 250 kpc (Haynes et al. 2007). Haynes et al. (2007) attribute this long tail to gas stripped from NGC 4254 by the process of galaxy harassment (Moore et al. 1996) as it enters the Virgo cluster at high speed. The presence of the large HI cloud VIRGOHI21 (Davis et al. 2004) which connects spatially and kinematically (Haynes et al., Minchin et al. 2005) to NGC 4254 resembles the results of the simulations by Bekki et al. (2005).

The X-ray emission detected from this galaxy (Chyzy et al. 2007, Soria & Wong 2006) is confined to the optical disk. This indicates the absence of hot gas around NGC 4254 which is as expected since it is located on the periphery of the Virgo cluster at a projected distance of 1.2 Mpc from M87. Soria & Wong (2006) suggest that the ultraluminous X-ray (ULX) source they detect due south of the optical disk of NGC 4254 has been triggered by the impact of the infalling HI cloud (Phookun et al. 1993) on the disk.

5.1 Origin of the extended radio continuum emission

Edge-on galaxies commonly show the presence of halo emission extending along the minor axis which is widely studied at low radio frequencies owing to their steep spectra. We examined the DSS maps of a few low inclination galaxies (e.g. NGC 5236, NGC 2997, NGC 6946) taken from the atlas by Condon et al. (1987) and find that the radio and optical disks have similar extents. Hence we find the radio continuum envelope detected around NGC 4254 interesting and in this section we try to understand the origin of the extended component (Fig. 3). We believe one of the following scenarios can account for this extended radio continuum component.

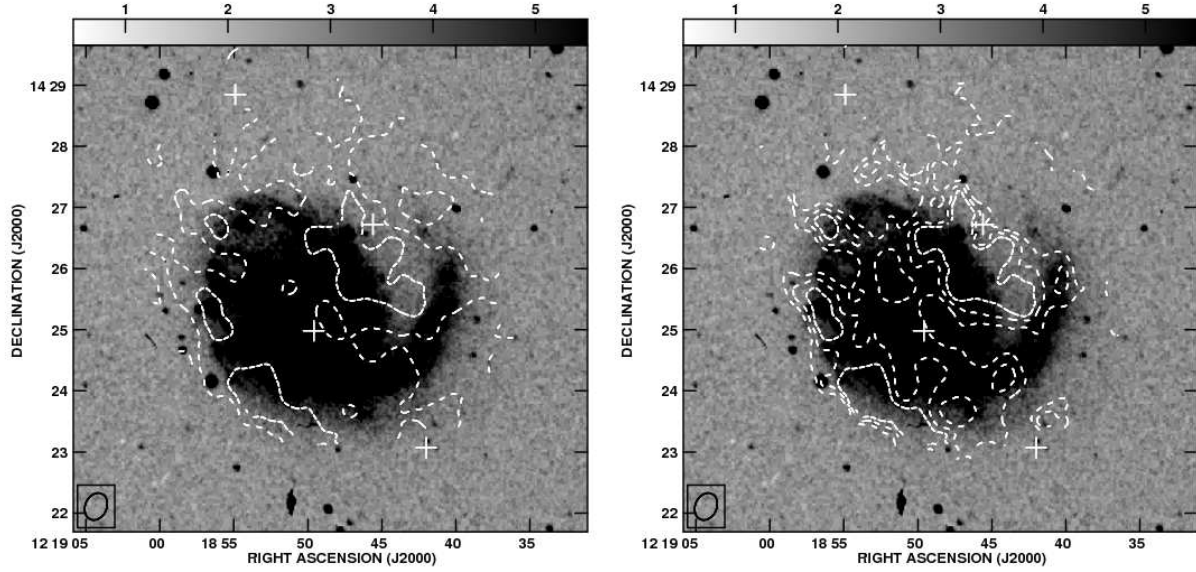


Figure 6. Spectral index maps of NGC 4254. The maps were convolved to a resolution of $27.4'' \times 21.1''$, $PA = -24^\circ$ and a flux cutoff of 2σ was used. The spectral index contours are superposed on the DSS optical image. The solid lines outline regions which are blanked or show positive spectral index whereas the dashed line indicate the negative spectral index distribution. The crosses mark the position of the centre of the galaxy and three background sources which have been removed from the images. (a) Left panel shows contours for $\alpha = -2, -1$ which is typical of the gas beyond the optical disk. (b) Right panel shows contours for $\alpha = -0.8, -0.4$ which is typical of the disk gas.

5.1.1 Extension of spiral arms

If we examine Fig 3b closely, it appears that the radio emission extends further along the spiral arms of the galaxy especially in the north-west and south-east. Thus, one possibility is that the spiral arms extend further out in the radio than in the optical. We examine the plausibility of this as follows. The typical synchrotron lifetimes of relativistic electrons diffusing out from supernovae in the galaxy would be 4×10^8 years at 240 MHz if the magnetic field was $3 \mu\text{G}$. Since we observe radio continuum emission from the envelope, this suggests that the relativistic electron population was generated less than 4×10^8 years ago. If this was the case, then at least the low mass stars (lifetimes $> 4 \times 10^8$ years) from the progenitor stellar population should be surviving even if the OB associations have disappeared (lifetimes $\sim 10^6$ years) during the synchrotron lifetime of the electrons. However no optical emission in the DSS R band is observed to be coincident with the extended features. We also examined the NIR emission in the J, H and K bands from the 2MASS maps which trace emission from low mass stars. The NIR morphology of the galaxy is similar to the DSS optical and no emission coincident with the extended features is detected. This indicates that the extended features are unlikely to be extensions of the galactic spiral arms but are a result of some other physical processes.

5.1.2 Emission from ram-pressure stripped gas

The extended emission could be from the magnetized electron gas which has been removed from the disk due to external influences like tidal, ram pressure or turbulent viscous stripping. This would lead to the ICM being enriched in magnetic field and matter.

Our multi-frequency radio study of NGC 4254 gives interest-

ing results. We detect radio continuum emission from regions surrounding the optical disk (see Fig 3). The spectrum of this emission is steeper ($\alpha \leq -1$) compared to the disk emission ($\alpha \geq -1$). Moreover, the extended emission does not form a uniform halo around the optical disk (see Fig. 1). While it could be partially attributed to sensitivity and spatial frequency coverage, most of this feature indicates real asymmetry in the extended emission. At 240 MHz, about 15% of the total emission arises in this extended component. In our HI velocity map, we notice a lagging rotation field in the atomic gas located to the north of the galaxy. It is likely that this part is being stripped and the gas is slowly losing rotation.

From the above, we suggest that the extended radio continuum emission which has a steeper spectral index and the atomic gas in the north of the galaxy are likely not part of the disk emission and probably do not lie in the plane of NGC 4254. This might be gas which has been pushed out of the galaxy by ISM-ICM interaction. Below we summarize the morphological features that we believe can be explained by ram pressure caused by the ISM-ICM interaction:

- A sharp cutoff is present in both the radio continuum and HI to the south/south-east. The galaxy is ploughing into the ICM at an angle of 70° (Vollmer et al. 2005) which is close to face-on and the south is the leading edge encountering the ICM wind. The swept-up gas would, thus, give rise to such a smooth boundary.
- The enhanced star formation rates across the entire galaxy. The wind encounters the entire disk and hence star formation would have been triggered throughout the disk explaining the enhanced star formation rates ($\sim 10 M_\odot \text{yr}^{-1}$, Soria & Wong 2006)
- Intense radio emission. This would be a direct result of enhanced star formation and presence of young massive stars in this galaxy.

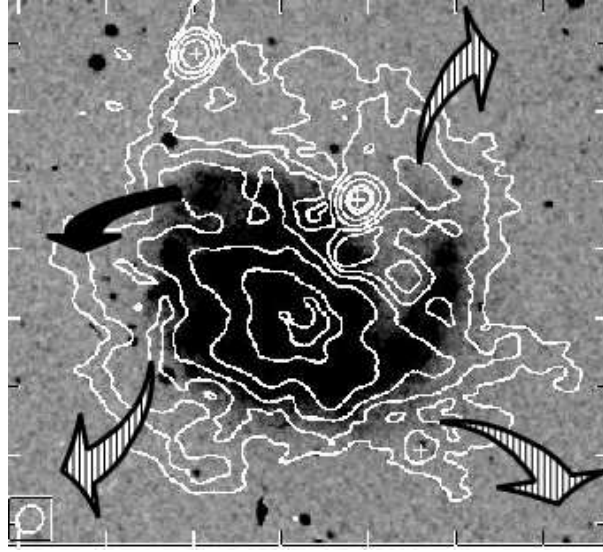


Figure 7. Schematic explaining the origin of the extended emission around NGC 4254 observed in radio continuum at 240 MHz. The 240 MHz map in contours alongwith the optical DSS map are shown. The arrows (white with black stripes) indicate the expanding envelope around NGC 4254 whereas the black arrow shows that the galaxy is moving southwards and into the page. The schematic is not to scale. The envelope of expanding gas is between us and the galaxy as the galaxy recedes with a velocity of 1300 km s^{-1} towards the cluster centre.

- Extended radio continuum around the optical disk. This emission is from the relativistic electron gas which has been influenced by ram pressure and which is subsequently diffusing beyond the galaxy as the latter rushes towards the cluster centre (see Fig. 7) through the ICM. The extended emission arises in gas which is not co-planar with the disk of the galaxy but follows the galaxy. The HI Tully-Fisher relation gives a distance of 16.8 Mpc to NGC 4254 (Schoniger & Sofue 1997) whereas the mean distance to the Virgo cluster is 20.7 ± 2.4 Mpc (Federspiel et al. 1998). Thus, NGC 4254 is closer to us compared to M87 and hence it is reasonable to consider it to be receding and falling in towards the centre of the cluster. The matter giving rise to the extended radio continuum, then, lies between us and the galaxy.

- Steep spectrum of the extended continuum. The extended emission is similar to the halo emission observed in edge-on disk galaxies which is also found to have a steeper spectrum compared to disk emission. We believe a similar explanation holds for the emission around NGC 4254.

- Extended polarized envelope at 1.4 GHz detected around the optical disk by Chyzy et al. (2006, 2007).

- Minor HI deficiency of 0.17 quoted by Cayatte et al. (1994).

Based on the above, we believe that the extended radio continuum emission detected outside the optical disk is mainly because of a ram pressure event as the galaxy moves in the ICM. The point we would like to stress is that ram pressure is effective even though the galaxy is located in the low ICM density environs in the outskirts of the Virgo cluster.

Using equipartition and minimum energy arguments, we find that the equipartition magnetic field in NGC 4254 is about $3 \mu\text{G}$ and the magnetic pressure is $4 \times 10^{-13} \text{ ergs cm}^{-3}$. The ram pressure acting on the galaxy, which lies about 3.7° from the centre of the cluster was estimated to be $9 \times 10^{-13} \text{ ergs cm}^{-3}$ (Cayatte et al. 1994). They estimate the gravitational pull for this galaxy to be $16 \times 10^{-13} \text{ ergs cm}^{-3}$. Thus, the ram pressure acting on the galaxy leading to gas stripping is slightly larger than the magnetic pressure holding back the relativistic electrons from escaping and

about half of the gravitational pressure of the galaxy. Since this galaxy has undergone a tidal encounter, the tidal debris could increase the ICM densities or the tidal interaction could have reduced the surface density of gas in the outer parts of the galaxy leading to an enhancement in the ability of ram pressure to influence the ISM of NGC 4254. Similar mechanism has been suggested for other Virgo galaxies (e.g. Vollmer 2003, Chung et al. 2007) and poor groups (e.g. Kantharia et al. 2005). Moreover the high star formation rate of the galaxy would lead to intense stellar winds and supernova explosions which would further facilitate the ISM-ICM interaction. Thus, we believe that our radio observations support the earlier results of Vollmer et al. (2005) and Chyzy et al. (2006) where both tidal interactions and ram pressure were put forward to explain the observed morphology of the HI and the radio continuum at 1.4 and 4.8 GHz of NGC 4254. We also suggest a possible way to determine whether a low inclination galaxy has undergone a ram pressure event by examining its low radio frequency morphology and the distribution of the spectral index across it.

5.2 Comparison with published simulation results

Several authors have studied ram pressure stripping in a variety of environs and with a variety of initial conditions in clusters and groups (e.g. Schulz & Struck 2001, Vollmer 2001, Roediger & Hensler 2005, Roediger & Bruggen 2006, Hester 2006). We examine these in light of our new low frequency radio observations of NGC 4254. The angle between the disk of NGC 4254 and its orbital plane in Virgo cluster is 70° (Vollmer et al. 2005) and the stripping is close to, but not entirely, face-on as the galaxy moves within the cluster. Roediger & Bruggen (2006), in their simulations of ram pressure stripping in disk galaxies, have shown that for face-on stripping, the stripped gas will expand and form a tail behind the galaxy. For a low inclination galaxy, the stripped gas will form a halo around it over a few hundred million years and would be detectable depending on its emissivity. Vollmer et al. (2005) performed simulations to explain the observed HI morphology (Phookun et al. 1993) of NGC 4254. They could explain most

of the morphological features only if ram pressure is invoked along with a tidal encounter which would have occurred about 300 Myrs ago. Their results indicated that ram pressure would only succeed in distorting gas with hydrogen column densities $< 10^{20} \text{ cm}^{-2}$. Roediger & Hensler (2005) and Roediger & Bruggen (2006), from their simulations on the influence of the ICM on the cluster members, infer that galaxies undergo ram pressure stripping in three stages. The first stage, they describe as the instantaneous stripping phase wherein the outer gas disk expands without becoming unbound from the galaxy. It can lead to truncation of the gas disk without much mass loss. This phase is likely to affect galaxies on the outskirts of clusters and in groups and is short-lived, lasting only for 20 to 200 Myr. In the intermediate, much longer-lived phase, some of the expanded gas actually evaporates while some of it falls back on the disk. In the final third phase, the galaxy loses mass at a stable rate of $1 M_{\odot} \text{ yr}^{-1}$ due to turbulent viscous stripping (Nulsen 1982).

Comparing this simulation result with our radio continuum data on NGC 4254, it appears that gas stripping in NGC 4254 is in the first phase of evolution. The extended features which surround the optical disk of NGC 4254 (see Fig. 3) are probably due to the relativistic gas which has diffused out from the disk but has not yet evaporated. The same argument also probably holds for the HI gas. The gas is being stripped as seen from the jagged morphology of HI that we detect especially in the north and along the vertical edge in the east. The smooth boundary to the south is the leading edge and is caused by the wind blowing across it. Some of the gas in the north which shows a lagging rotation field might be due to stripped gas which is slowly losing rotation. We also tried to understand the non-disk HI clouds that Phookun et al. (1993) have detected surrounding the galaxy and not following galaxy rotation. Phookun et al. (1993) conclude that these clouds form an infalling population. While the tidal origin put forward by Phookun et al. (1993) is the most plausible especially since these form part of the long HI tail which Haynes et al. (2007) attribute to galaxy harassment, we examined it in relation to the three stages of ram pressure stripping inferred by Roediger & Hensler (2005) and explained in brief above. If we hypothesize that the infalling clouds were stripped from the galaxy due to ram pressure then the HI gas in this galaxy might have just entered into the second phase of evolution (Roediger & Hensler 2005). In this phase, part of the HI falls back whereas part of the gas is lost from the system. Some of the far non-disk HI clouds that Phookun et al. (1993) detect could also possibly be part of this population. Since the galaxy is receding towards south/south-east, the tail of clouds extending northwards appears to be in the expected direction. However, we also note that Roediger & Bruggen (2006) demonstrate in their simulations that the direction of motion of the galaxy cannot always be surmised from the tail of stripped gas. It may be mentioned, however, that our explanation of the infalling clouds (Phookun et al. 1993) is more speculative and requires further evidence from simulations.

Since NGC 4254 is located in a relatively low density environment in the outskirts of the Virgo cluster, the ram pressure stripping event is relatively young and was begun at most 200 Myrs ago (Roediger & Hensler 2005). Recall that the simulation by Vollmer et al. (2005) indicated that a tidal interaction involving NGC 4254 occurred ≈ 300 Myrs ago. These timescales support the hypothesis that the tidal encounter boosted the potential of ISM-ICM interaction making it more effective than it would have otherwise been. The schematic in Fig. 7 summarizes the scenario for NGC 4254 as discussed above.

6 SUMMARY & CONCLUSIONS

In this paper, we have presented multifrequency radio continuum observations made with the GMRT of the spiral galaxy NGC 4254 located in the north-west outskirts of the Virgo cluster. NGC 4254 is a luminous galaxy with a radio power of $7 \times 10^{22} \text{ Watts-Hz}^{-1}$ at 240 MHz. We report the detection of extended, structured, low surface brightness radio continuum emission at 240 MHz surrounding the optical disk. We note that Chyzy et al. (2006,2007) have reported detection of an extended polarized envelope around the optical disk at 1.4 GHz.

Combining our data with existing spectral data (Soida et al. 1996, Chyzy et al. 2007), we find that the best fit to the global spectrum is given by a spectral index of -0.848 ± 0.016 which is close to the value Soida et al. (1996) quote. However from our data at 240, 325 and 610 MHz, we deduce that the spectrum flattens at the lower frequencies. A heuristic model which includes electron propagation effects (Hummel 1991) gives a better fit to the data. The injection spectrum has an index $\alpha_0 = -0.45 \pm 0.12$.

From a detailed spectral index mapping between 240 and 610 MHz, we find that the spectral index of the extended emission is steeper with $\alpha \leq -1$ compared to that of the radio emission coincident with the optical disk ($\alpha \geq -1$). We hypothesize that the extended emission is not associated with the optical disk but has been pushed out due to ram pressure of the ICM acting on the ISM of the galaxy. The atomic material in the north lags in rotation wrt rest of the disk and this we believe is part of the gas mass which is being influenced by ram pressure. NGC 4254 is moving away from us and the stripped material lies between us and the galaxy as shown in the schematic of Fig. 7.

From the above, we conclude the following:

- We believe that we have detected a clear signature of ram pressure stripping in NGC 4254, a spiral galaxy in the outskirts of the Virgo cluster, in the form of an extended envelope of emission surrounding the optical disk at 240 MHz. This emission exhibits a steep spectral index as compared to the disk emission. We suggest that these might be common signatures of ISM-ICM interaction which have not been noticed due to a dearth of such low frequency high sensitivity data on low inclination galaxies in cluster/group environments.

- We suggest that low frequency (≤ 300 MHz) high sensitivity survey of a sample of face-on galaxies in low density groups and clusters will help generate significant information on the radio frequency signatures of ISM-ICM interactions. Signatures such as a steep spectrum and extended emission around low inclination galaxies can be studied for a larger sample.

- ISM-ICM interactions are likely to be more common in lower density, lower velocity dispersion environments than is presently believed. There are already several examples (e.g Solanes et al. 2001, Kantharia et al. 2005, Levy et al. 2007) which suggest that ram pressure events are active in X-ray poor groups and in the outskirts of clusters. Simulations by several groups (e.g. Roediger & Bruggen 2006, Vollmer et al. 2005, Hester 2006) show that this is possible. Ram pressure in many of these cases is aided by other physical phenomena such as tidal interaction and supernova explosions. The stripped gas would help enhance the ICM densities further. Systematic low frequency observations of several galaxies in the outskirts of clusters and in poor groups are required for further understanding.

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